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Autonomous Navigation and Obstacle Avoidance for Unmanned Surface Vehicles

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Unmanned Systems Branch

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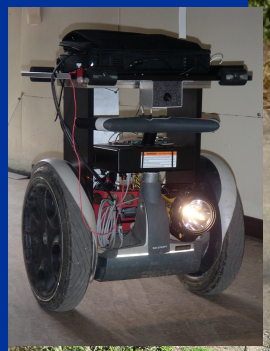
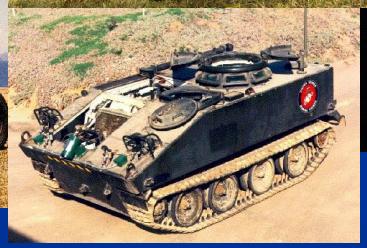
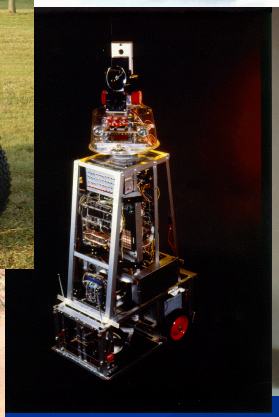
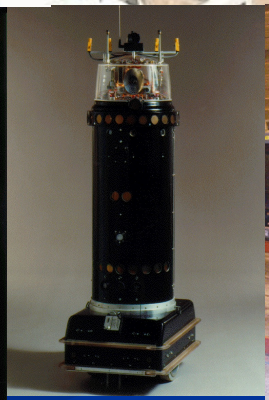
Topics of Discussion

- UGV background
- USV autonomy
- Sensors
- Command and Control
- Standards

SSC-SD UGV Background

- SSC San Diego has been developing autonomous UGVs for over 25 years
- Indoor, Outdoor, Small,
- Varying levels of autono



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UGV Autonomy

- Highly autonomous systems in very complex environments

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USV Development Platform

- In-expensive platform for developing the enabling technologies for USVs

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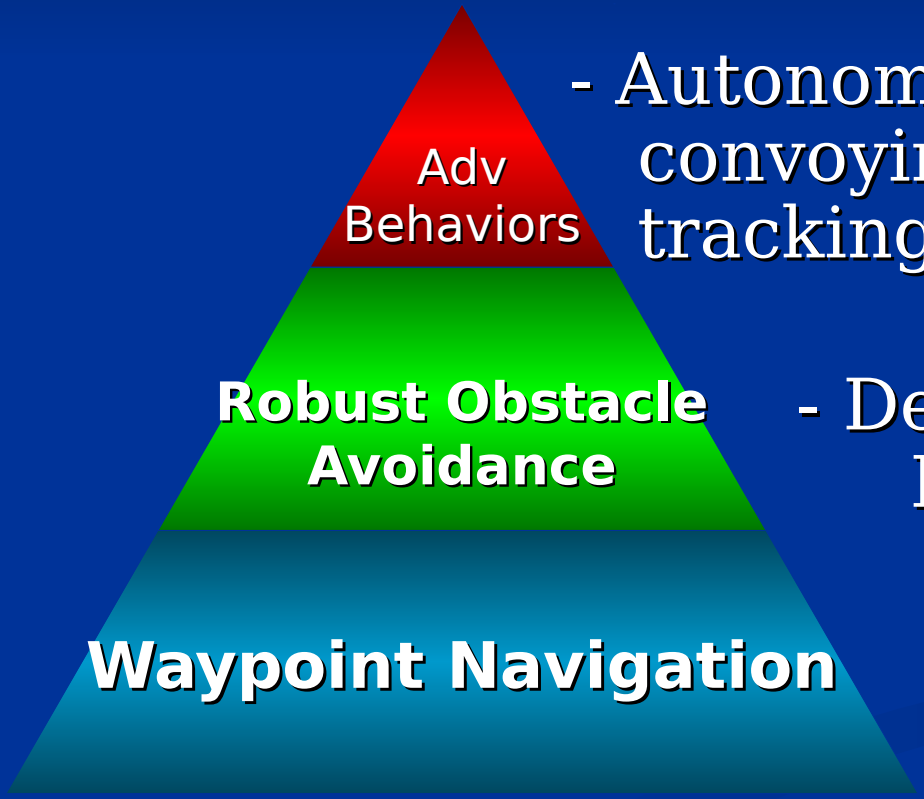
Approach to Autonomy

- Phased approach – focus on basic building blocks first



- Autonomous recovery, convoying, target tracking/interception

- Deliberative and Reactive

- Demonstrated

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Approach to Autonomy

- Phased approach – focus on basic building blocks first
  - Waypoint Navigation - demonstrated
  - Robust Obstacle Avoidance (OA) – focus of current effort
    - Autonomous path planning
    - Planning around moving obstacles (ARPA contacts)
    - Reactive near-field OA
  - Advanced behaviors
    - Autonomous recovery
    - Formation following
    - Autonomous target tracking, target interception

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Obstacle Avoidance Two-Tiered Approach

- Reactive OA in near field
  - Independent of USV mode of operation (tele-operation, waypoint nav, etc.)
  - Operates at same level and rate as the low-level navigation code
  - Modifies steering and throttle commands in real-time
  - Behavior based (CMU Morphin)
- Deliberative OA in far field
  - Modifies route to avoid contacts
  - Radar ARPA is the main data source for moving obstacles
  - Collects data from nautical charts for non-moving obstacles
  - Operates at rate of radar (or less)
  - Makes reactive OA easier

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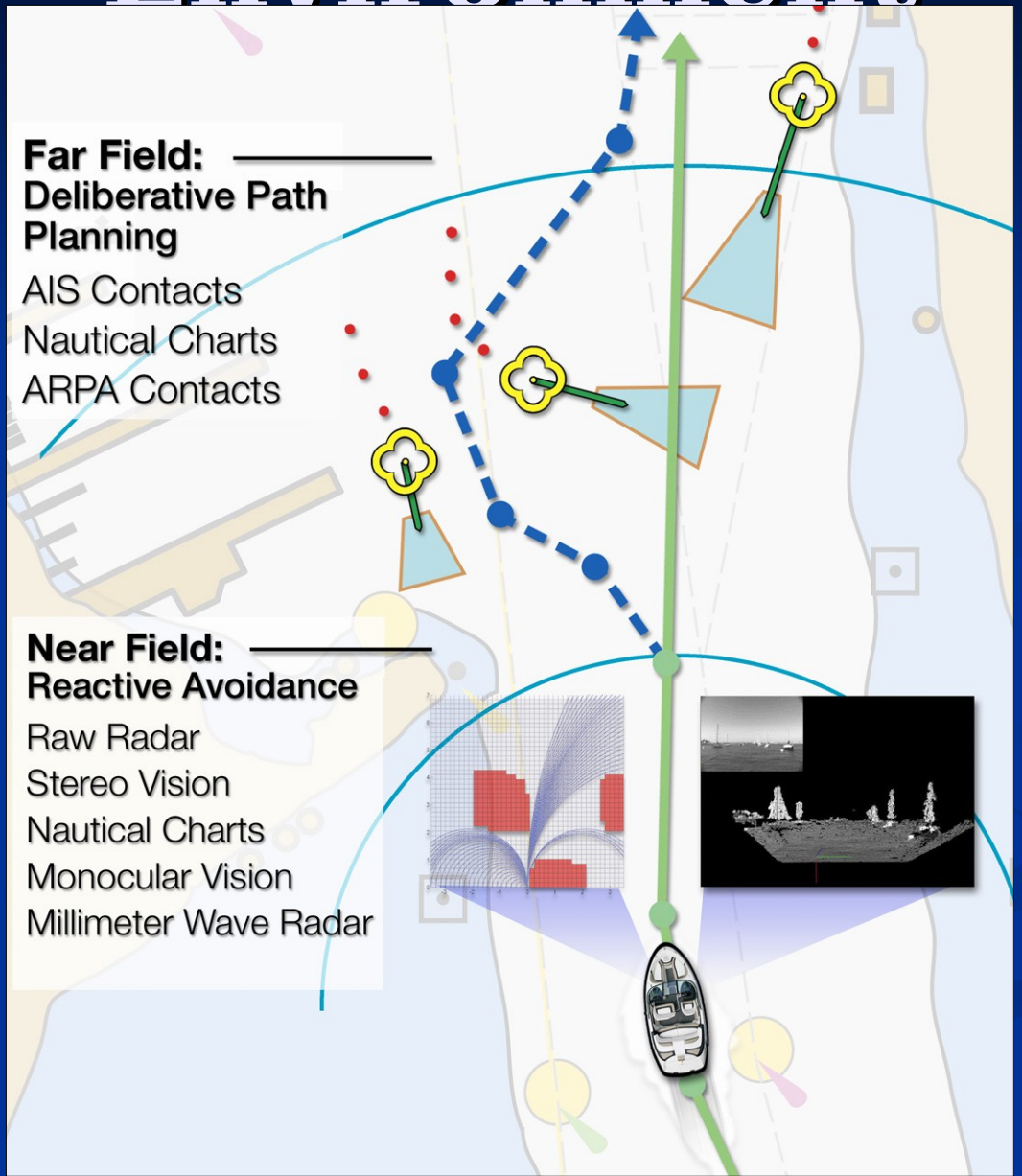
OA in Marine Environment



USV OA Software Architecture

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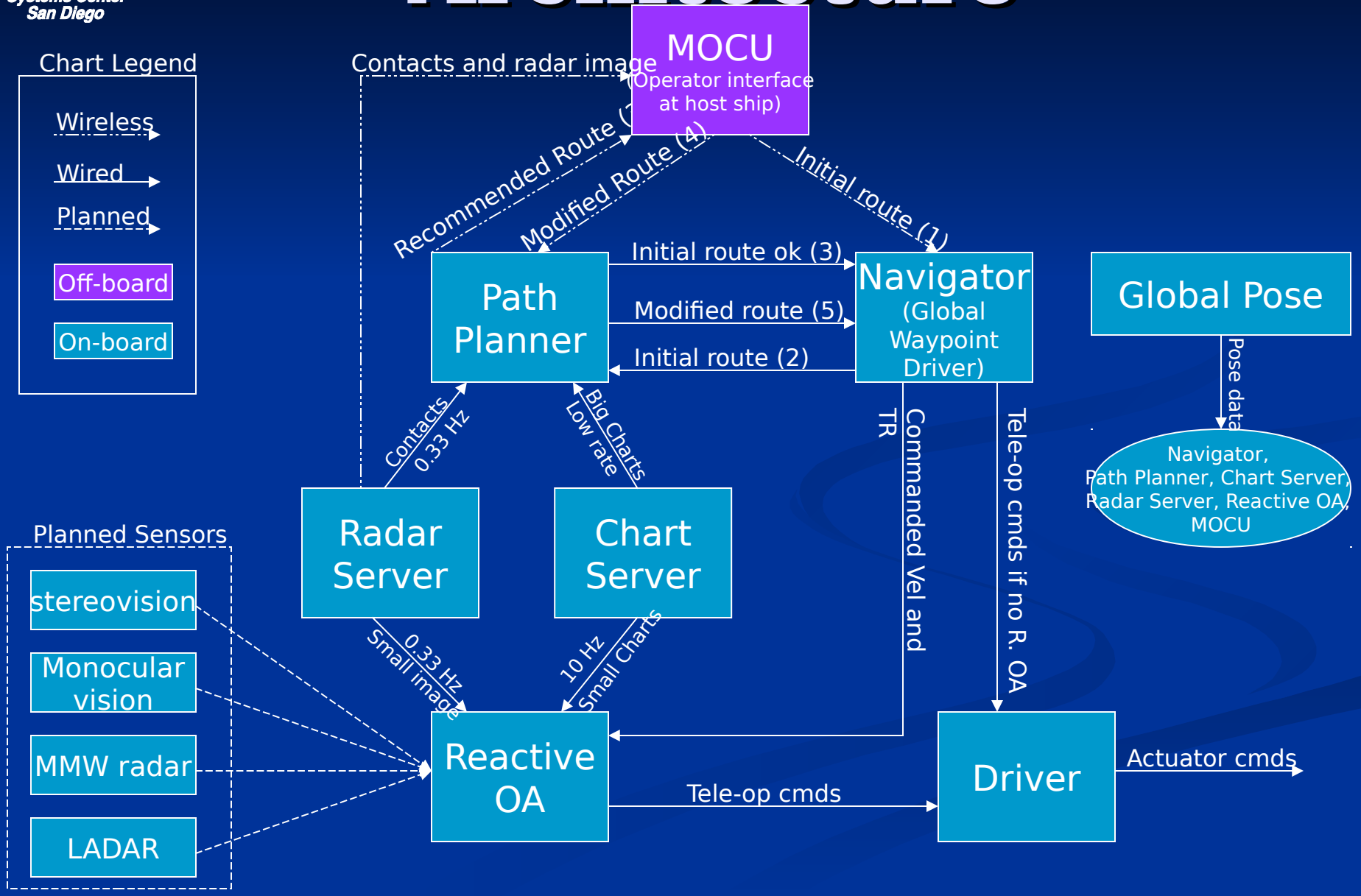

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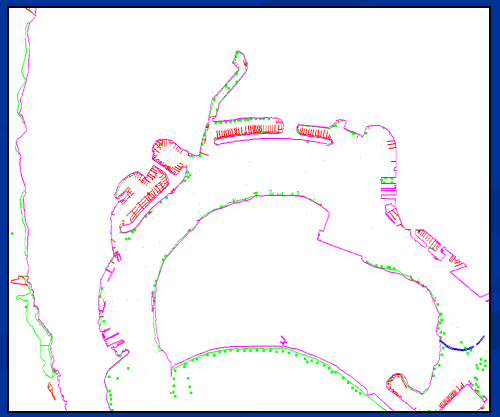
Deliberative OA

- Continuous path planning and re-planning
- Modifies original waypoint path to avoid obstacles
- Slow update rate (relies on radar contacts)
- Doesn’t guarantee obstacle avoidance
  - USV may not be on the path
  - Only works in waypoint mode
- Makes job of the reactive OA easier
- Can mimic rules of the road



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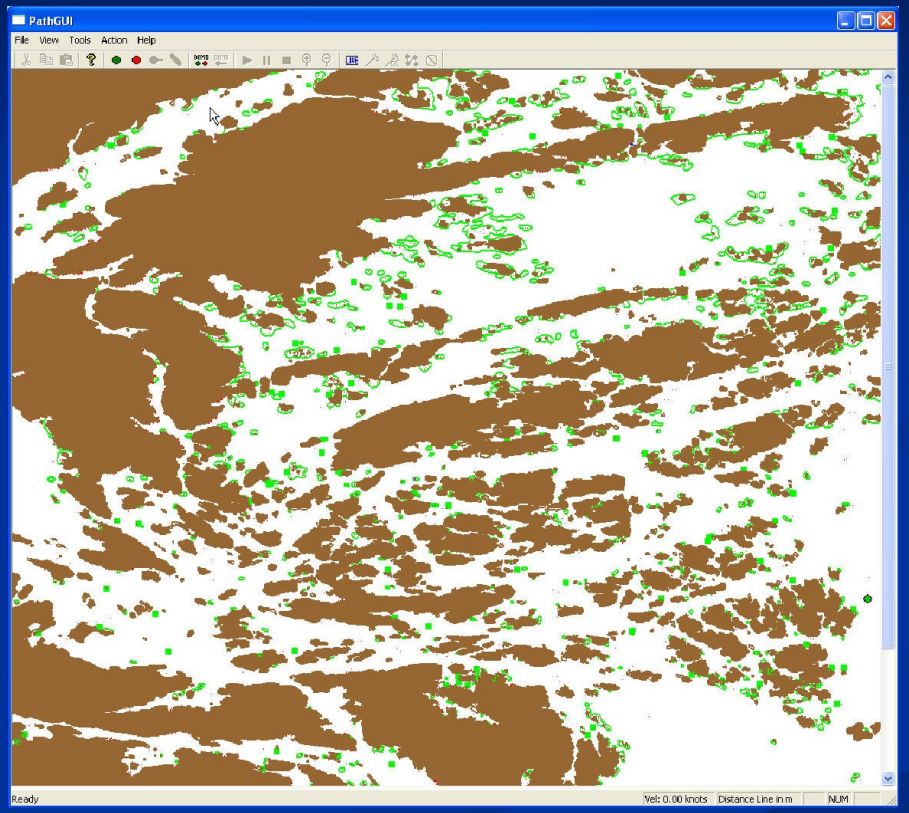
Path Planning

- A* search basis
  - Cost-focused exploration of grid space
    - Costs include path distance and proximity to obstacles
    - Obstacle-proximity cost variable provides means for setting a safety barrier around obstacles – different obstacles may have different safety barrier distances
    - Extendable to other costs (direction, shipping lanes, “soft” obstacles, route ETE, etc.)
- Path planning example northeast of Stockholm Sweden
  - 30m resolution grid



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Planning with Moving Obstacles

- Not trivial
- Where on the path is the contact going to actually represent a risk to the USV?
  - Use Velocity Obstacle (VO) method to calculate the velocities that cause a collision
    - Modifying USV velocity may result in the best or only path available
  - If VO doesn't work, create a new path around the obstacles
    - Quick calculations determine Closest Point of Approach (CPA)
    - Projected Obstacle Area (POA) represents obstacle area risk
    - POA determined by contact speed and heading +/- uncertainty values
      - Appropriate uncertainty values can mimic rules of the road

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Planning with Moving Obstacles

- USV chooses route of least cost from a number of routes that change velocity and/or course
  - Iterative process – find new route, re-calculate Projected Obstacle Areas, plan again if necessary (typically only requires 2-3 iterations)
- Path planning also corrects user errors
- Maintains as much of user defined route as possible
  - Follow user defined route (not least cost) unless obstructed
  - Revert back to user's route if obstruction no longer exists

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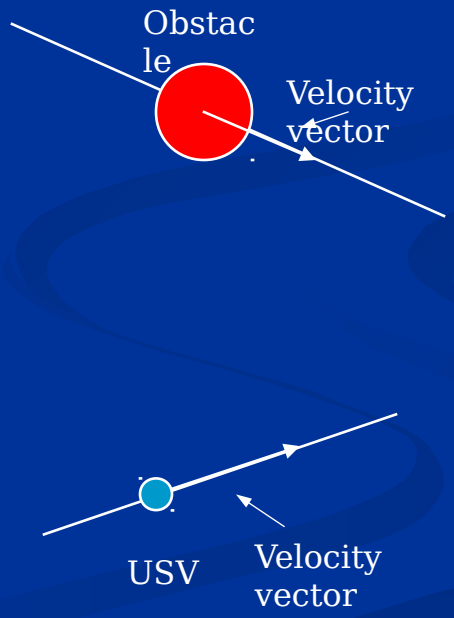
Velocity Obstacle

- A simple and efficient approach to compute the velocity and/or trajectory needed to avoid moving obstacles
- It transforms each moving obstacle into a stationary one by considering the relative velocity and trajectory of the USV with respect to the obstacle

The velocity and trajectory of the moving obstacle and the USV.



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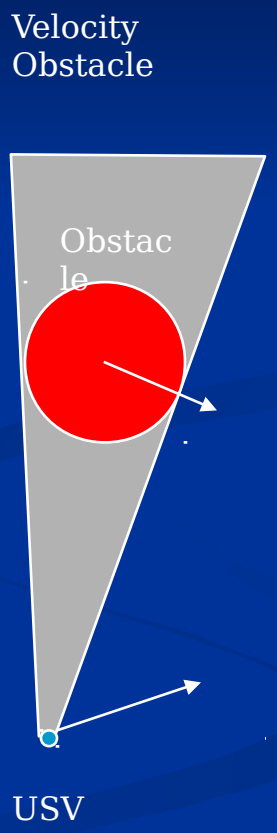
Velocity Obstacle

- First grow the area of the obstacle to account of a reasonable safety barrier
- Then map the USV and the obstacle to the USV's Configuration Space and, using the relative velocity, add the set of feasible velocities to build the Velocity Obstacle



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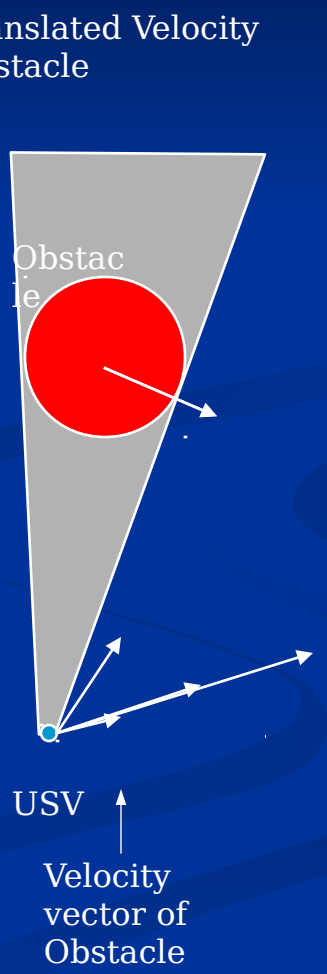
Velocity Obstacle

- Translate the Velocity Obstacle by the velocity vector of the obstacle
- If the tip of the USV's velocity vector lies inside the cone, there will be a collision
- To avoid collisions, decrease or increase the velocity, or set a new trajectory altogether



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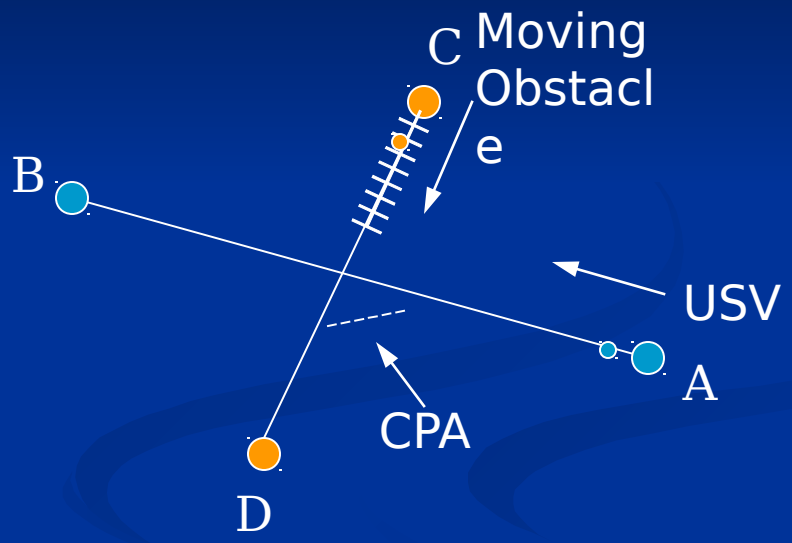
Closest Point of Approach (CPA)

- To find the CPA:
- Calculate a path segment for the moving obstacle using its heading, velocity, and the time for the robot to complete its own path segment
- Find the two points along the respective paths of both the robot and the moving obstacle, in relation to their headings and velocities, that returns the shortest distance.
  - This shortest distance is called the CPA



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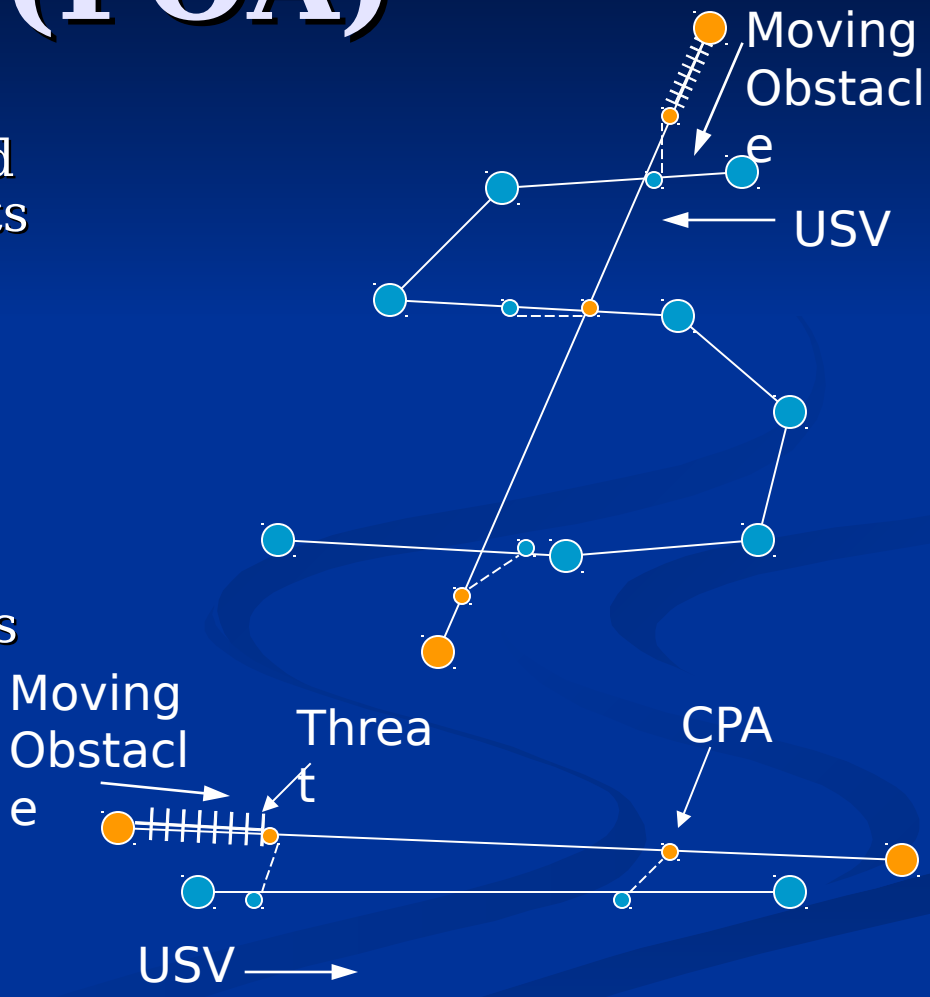
Projected Obstacle Area (POA)

- The CPA of a moving obstacle can be calculated for multiple path segments
- The two path segments don't have to cross to determine the CPA for a threatening moving obstacle
- The Path Planner is also aware of moving obstacles that pose a threat long before the CPA
  - It takes into account the point where the moving obstacle comes within some threat distance



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Projected Obstacle Area (POA)

- The future location of a contact has a degree of uncertainty that changes with time

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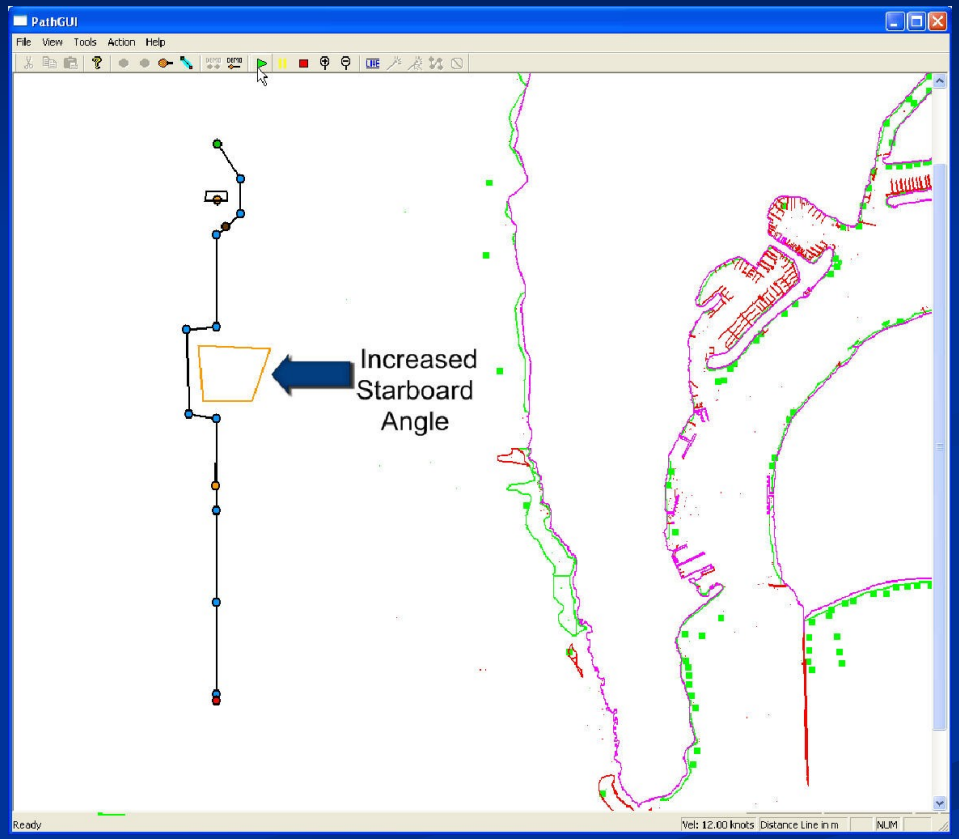
Rules of the Road

- Pass port-to-port when meeting head-to-head
- Follow direction of traffic flow
- Give right-of-way to other vehicles



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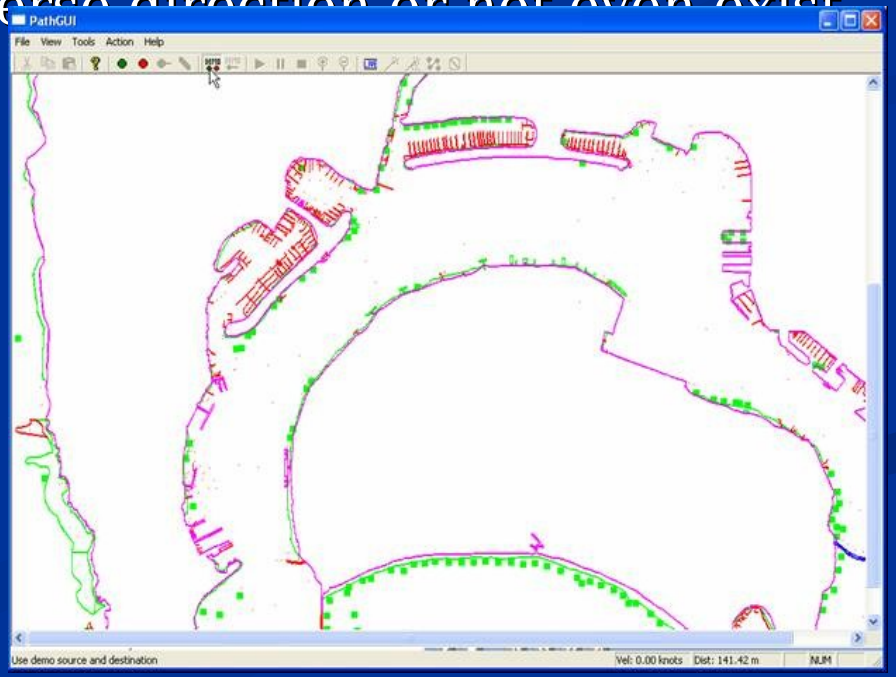
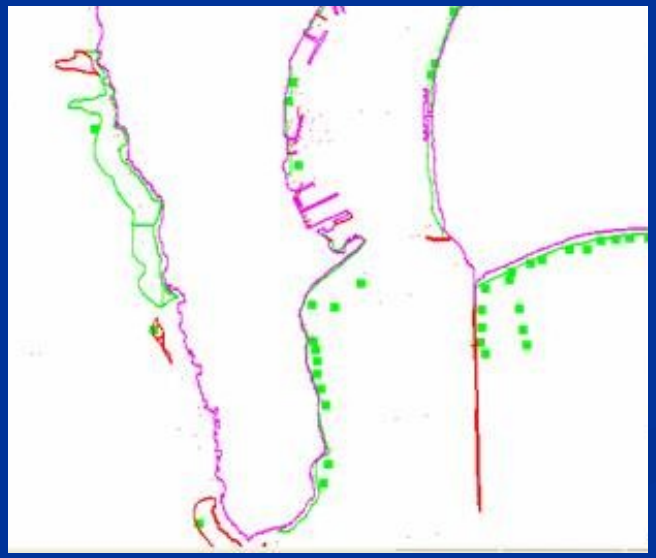
Maintain User-defined Route

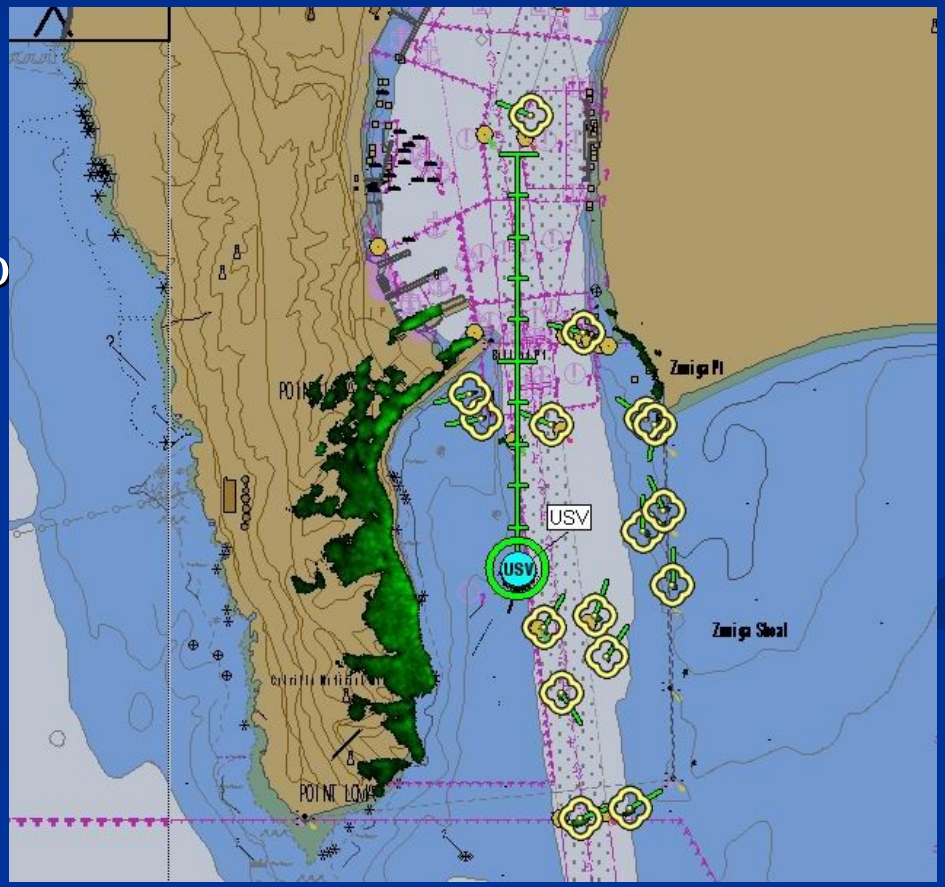
- Maintain user-defined route unless obstructed
  - Path of route is generally important
- Revert back to user's route if obstruction no longer exists
  - Contact may slow or reverse direction or not even exist



Deliberative OA Sensors

- Digital Nautical Charts (DNC)
- Networked marine radar
  - ARPA contacts
- Future plans
  - AIS
  - Bathymetry data
  - Host ship or shore side co





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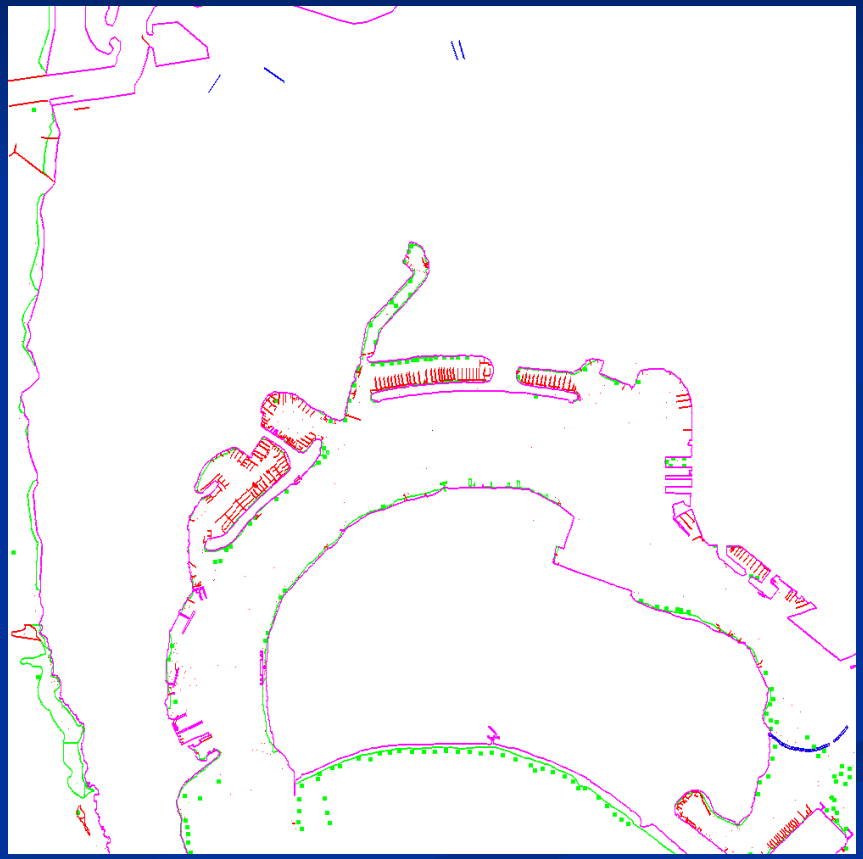
DNC - Data Conversion

- NGA Digital Nautical Charts
  - Embedded chart extraction and conversion on USV
  - Vector Product Format (VPF) data converted to an occupancy grid map
    - Coded according to type of obstacle
    - Data parsed to extract only true obstacles



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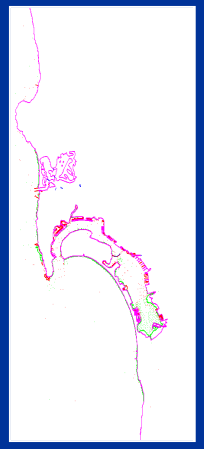
DNC - Map Resolution

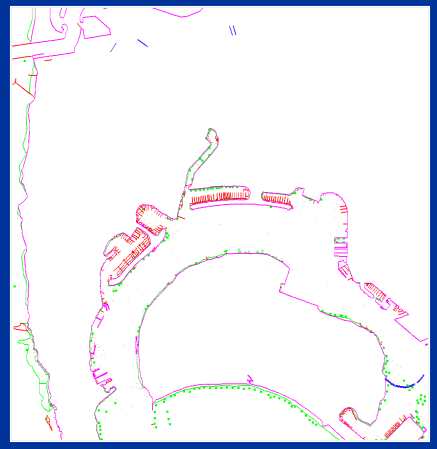
- VPF allows maps of varying resolutions

50x50

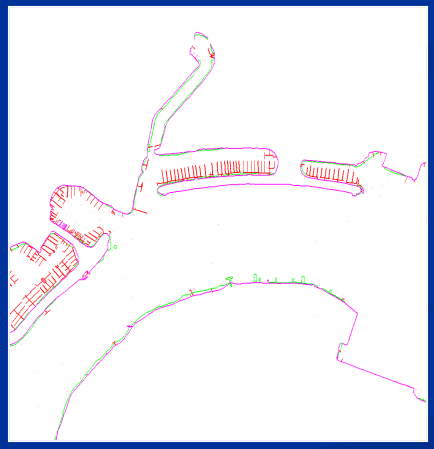


30x30

10x10



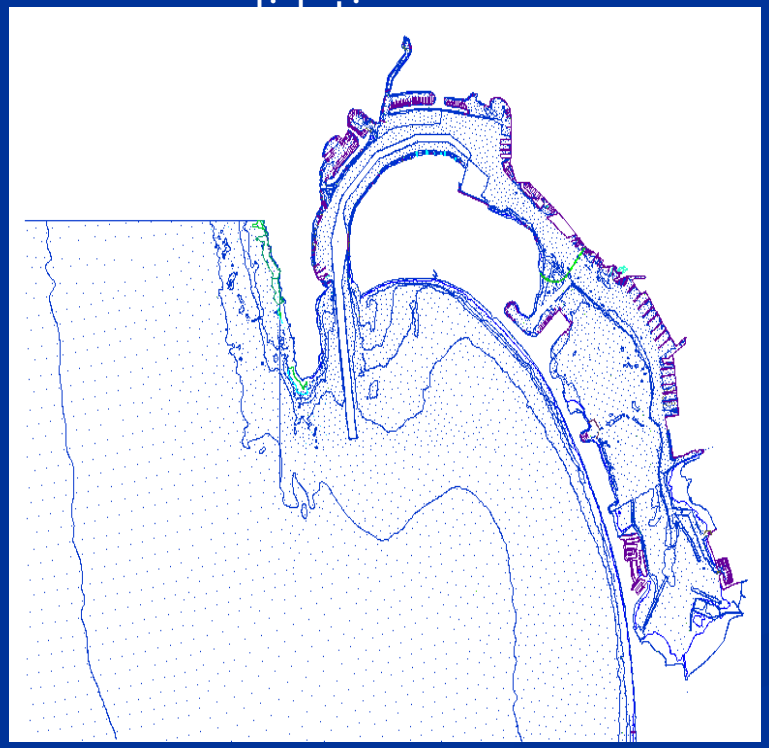
5x



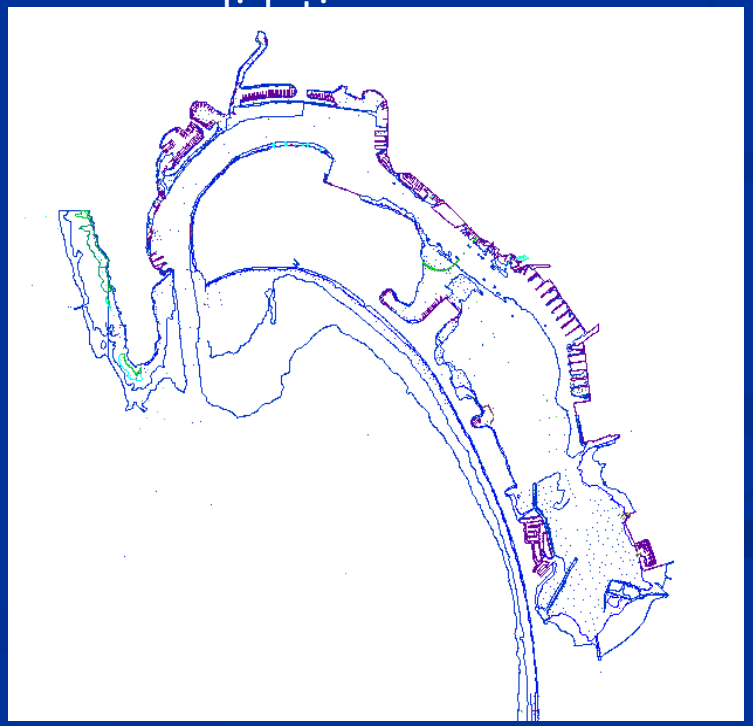
DNC - Feature Validation

- Parse through feature attributes and remove features that pose no serious obstacle threat

No feature



Feature



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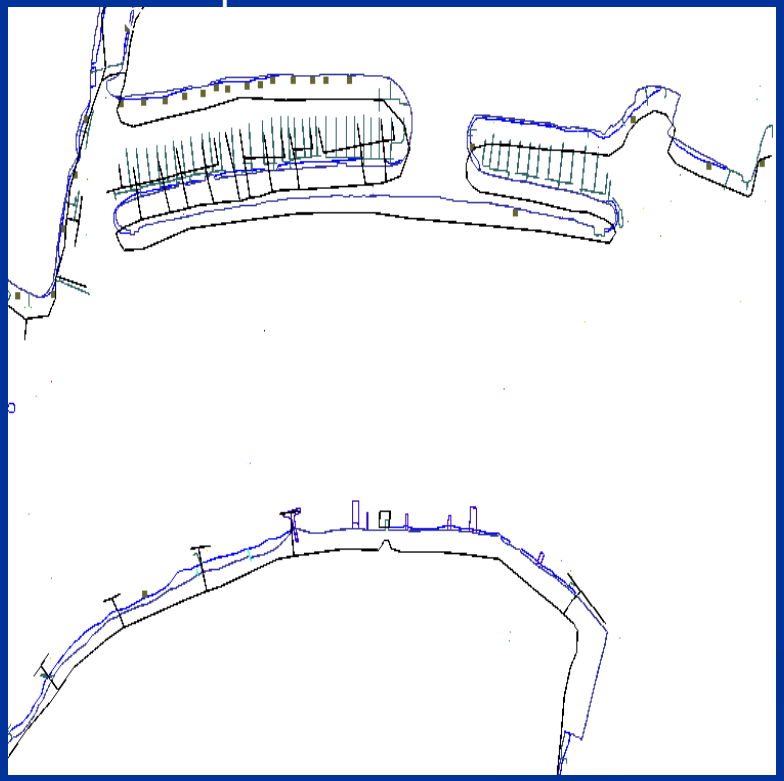
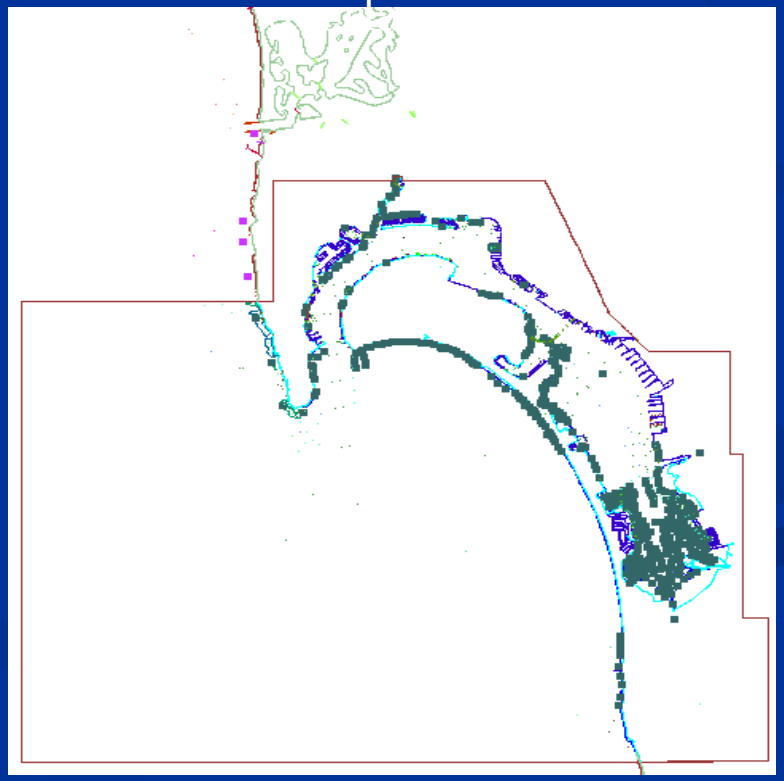
DNC - Data Overlap

- Merge overlapping and inconsistent harbor and approach data

Harbor and approach data



No



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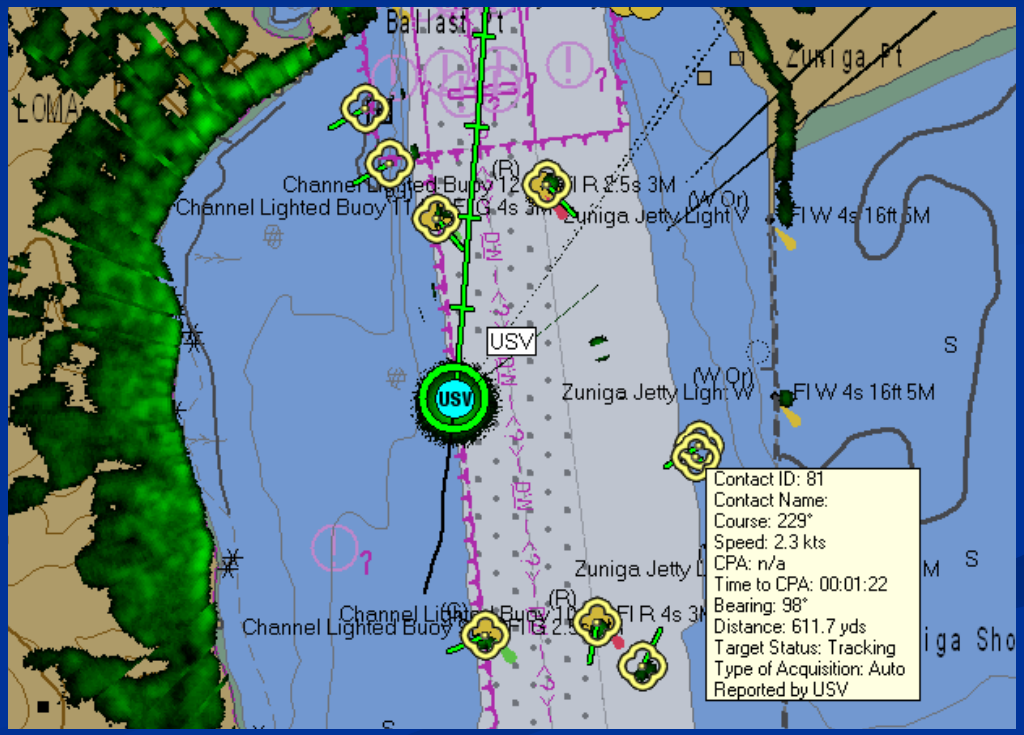
Radar – ARPA Contacts

- Networked marine radar
  - Xenex controller with a Furuno antenna
- Provides ARPA contacts
  - Position, speed and course of up to 100 contacts
- Issues
  - Data corrupted and contacts lost when USV turns at moderate rate
  - False contacts from shore
  - Distance to acquire small boats
  - Contact Acquire time



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Radar – Eliminate False Contacts From Shoreline

Radar – Contact Acquire Time

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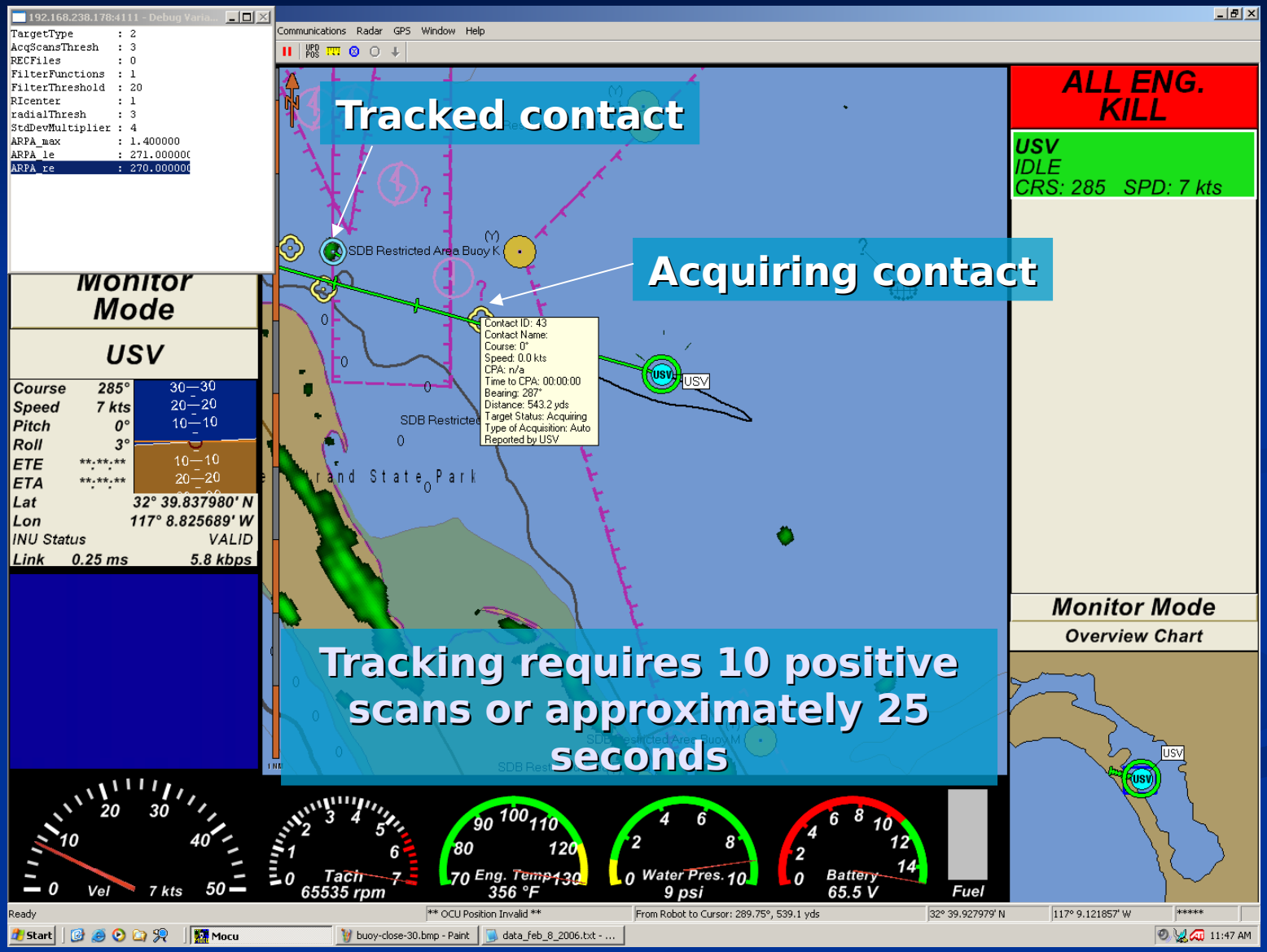

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Real World Path Planning Example

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Reactive OA

- Real-time trajectory modification
- Modifies throttle and steering commands at the same rate as the navigation system
- Common occupancy grid map
  - Sensor data is fused into a common data space
- Behavior based
  - Path following, OA, target tracking, etc.
  - Very easy to add new sensors and new behaviors
- Operates in arc space
  - Selects best arc each cycle
    - Arcs are defined by a speed and turn-rate
    - Given the desired arc and speed a required turn-rate is calculated

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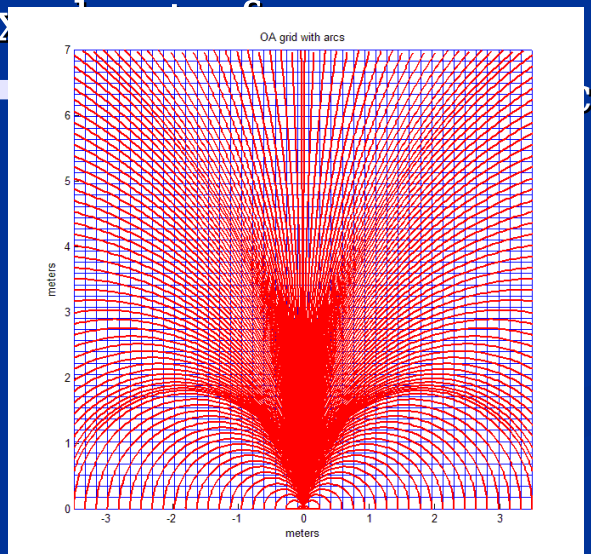
Reactive OA

- Loosely based on CMU Morphin algorithm and the Distributed Architecture for Mobile Navigation (DAMN)
  - Distributed behavior based system
    - Multiple behaviors vote on desired actions
    - Votes scaled from 1 to -1
  - Obstacle avoidance behaviors vote for or against a fix
    - cle speed and turn rate



$$R = \frac{V}{\dot{\theta}}$$

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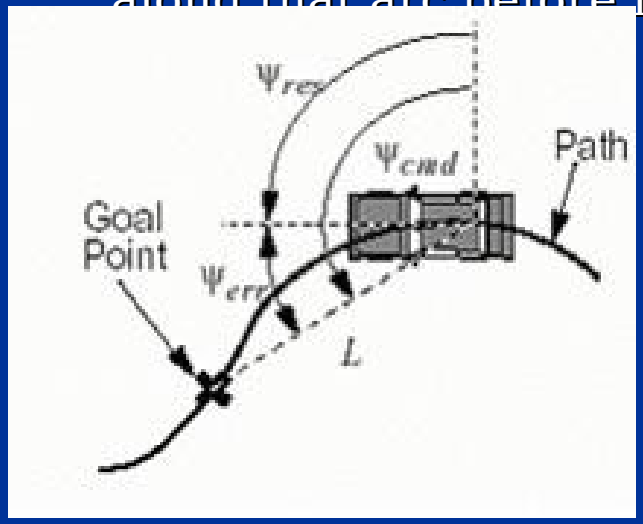
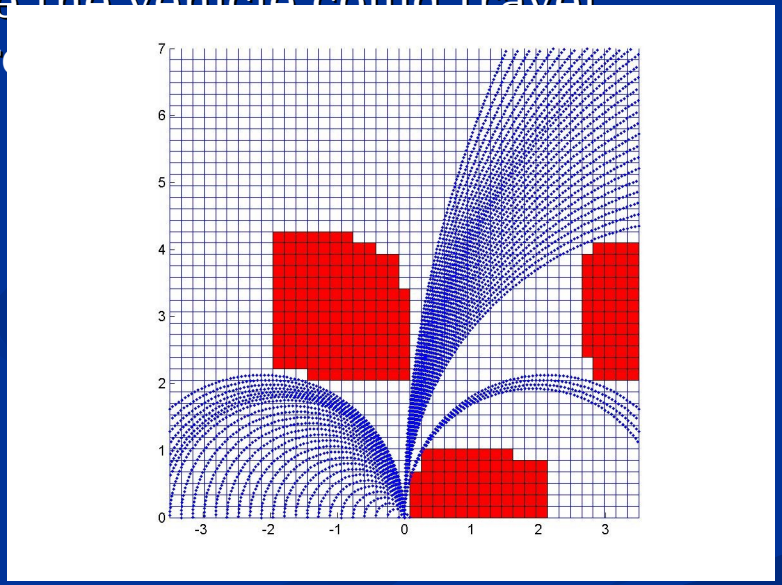
Reactive OA

- OA behavior votes against (0 to -1) arcs that are blocked
  - Vote is determined by the distance the vehicle could travel along that arc before it encounter





- Path following behavior votes for arcs (0 to 1) that are nearest the arc calculated by the waypoint navigation routine

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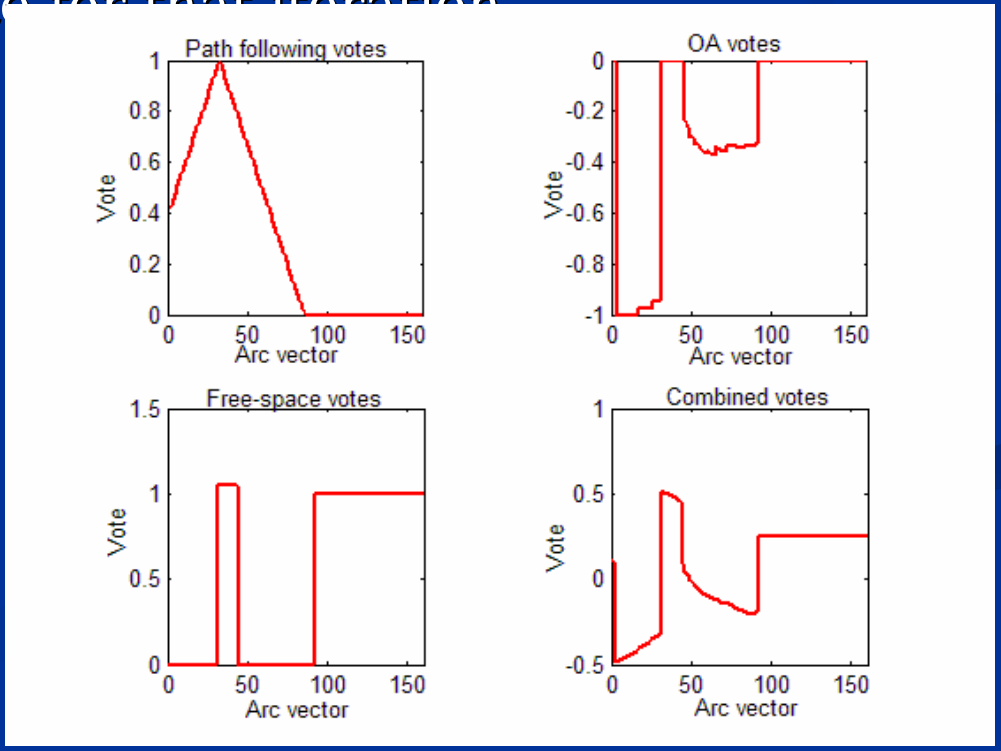
Reactive OA

- OA behaviors and arbiter
  - Arbiter combines weighted votes from all behaviors
  - Arc with highest vote is selected and used to set the velocity and turn rate for that iteration



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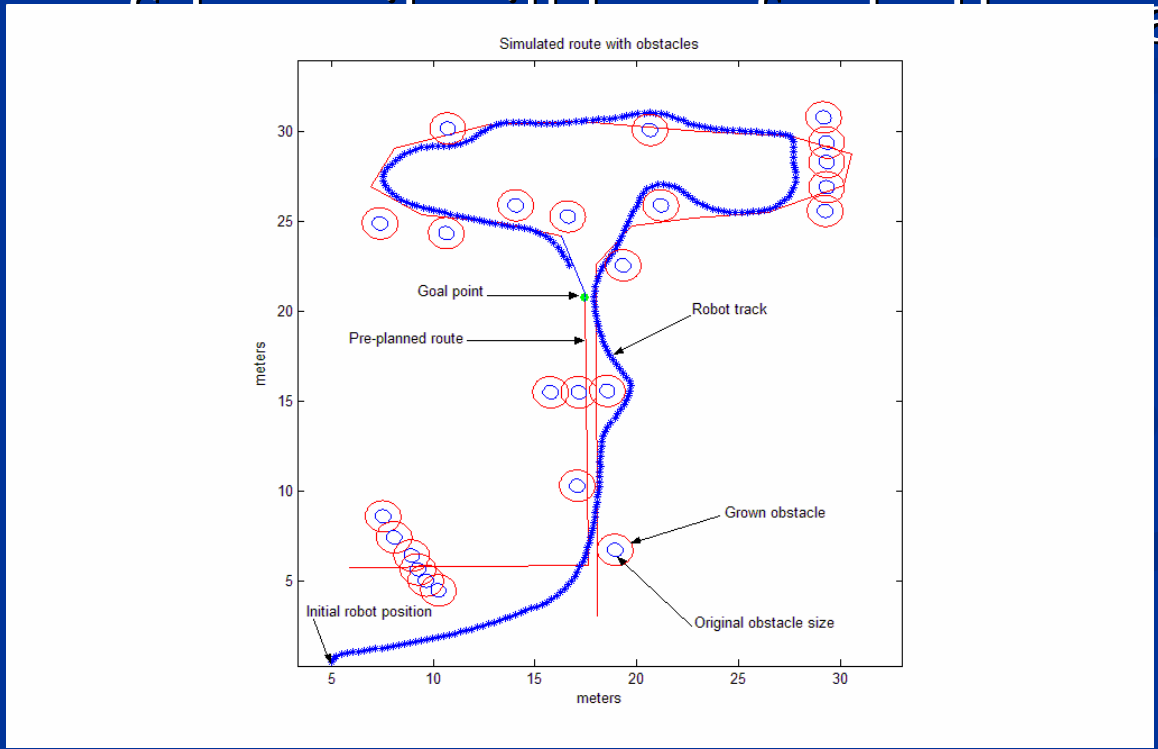
Reactive OA

- OA simulation in Matlab
  - Uses same URBOT simulator and route following code that was used to develop the waypoint navigation capability – fair degree of [illegible] al world



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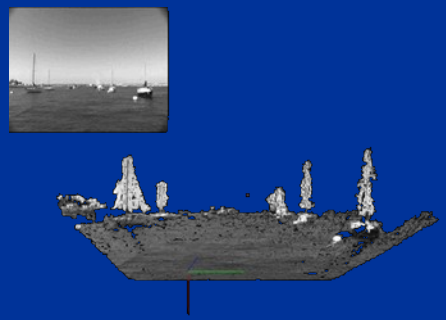
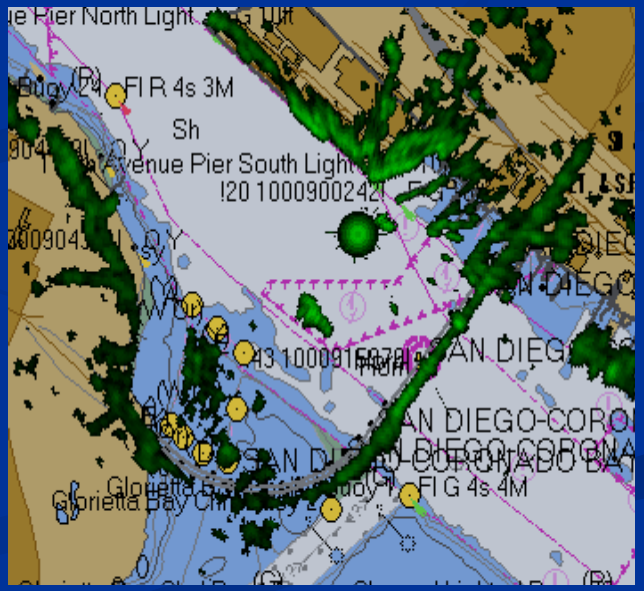
Reactive OA Sensors

- DNC data
- Raw radar
- Stereovision
- Monocular vision
- LADAR





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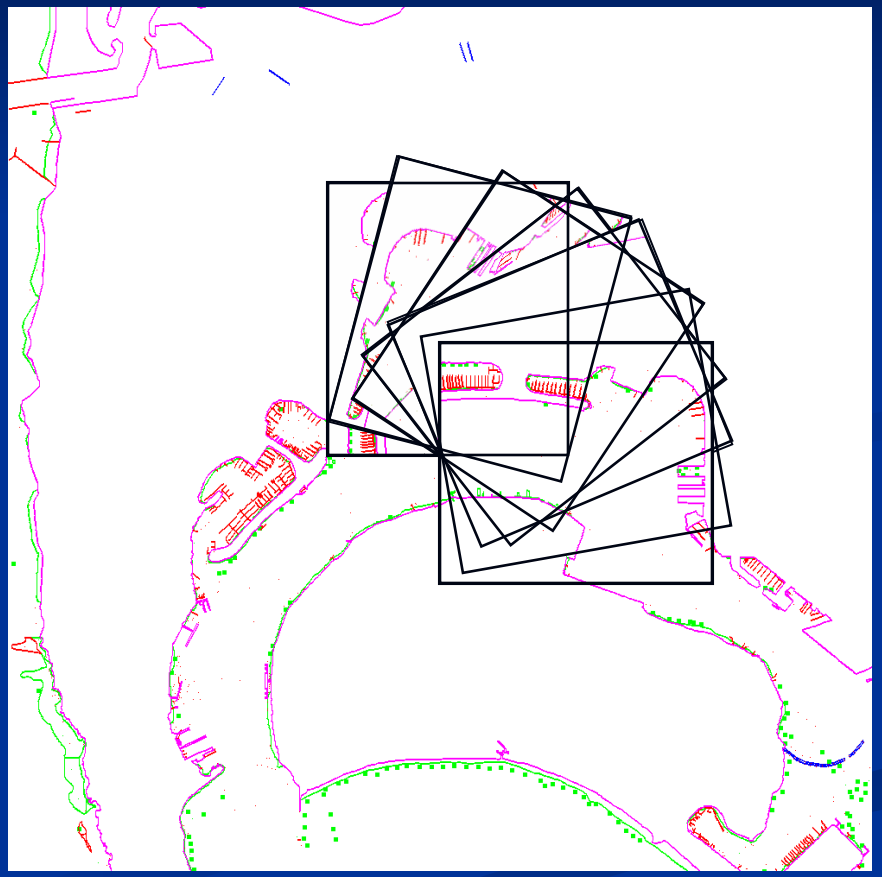
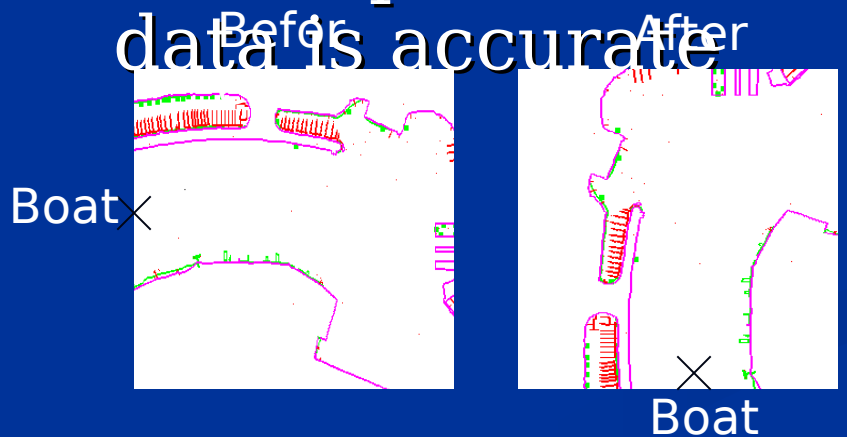
Reactive OA Sensors DNC data

- DNC data from the USV chart server
  - 10Hz update rates
  - Small local map oriented heading up for the USV
- Assumes that the USV's position data is accurate





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Reactive OA Sensors
Raw Radar

- Raw radar data from the USV radar server
  - 10Hz update rate
  - Small section of the radar image oriented heading up for the USV
    - Dead reckoned between radar updates
    - Converted from polar grid to Cartesian grid
  - Image processing performed to eliminate noise and extract useful data from center disk

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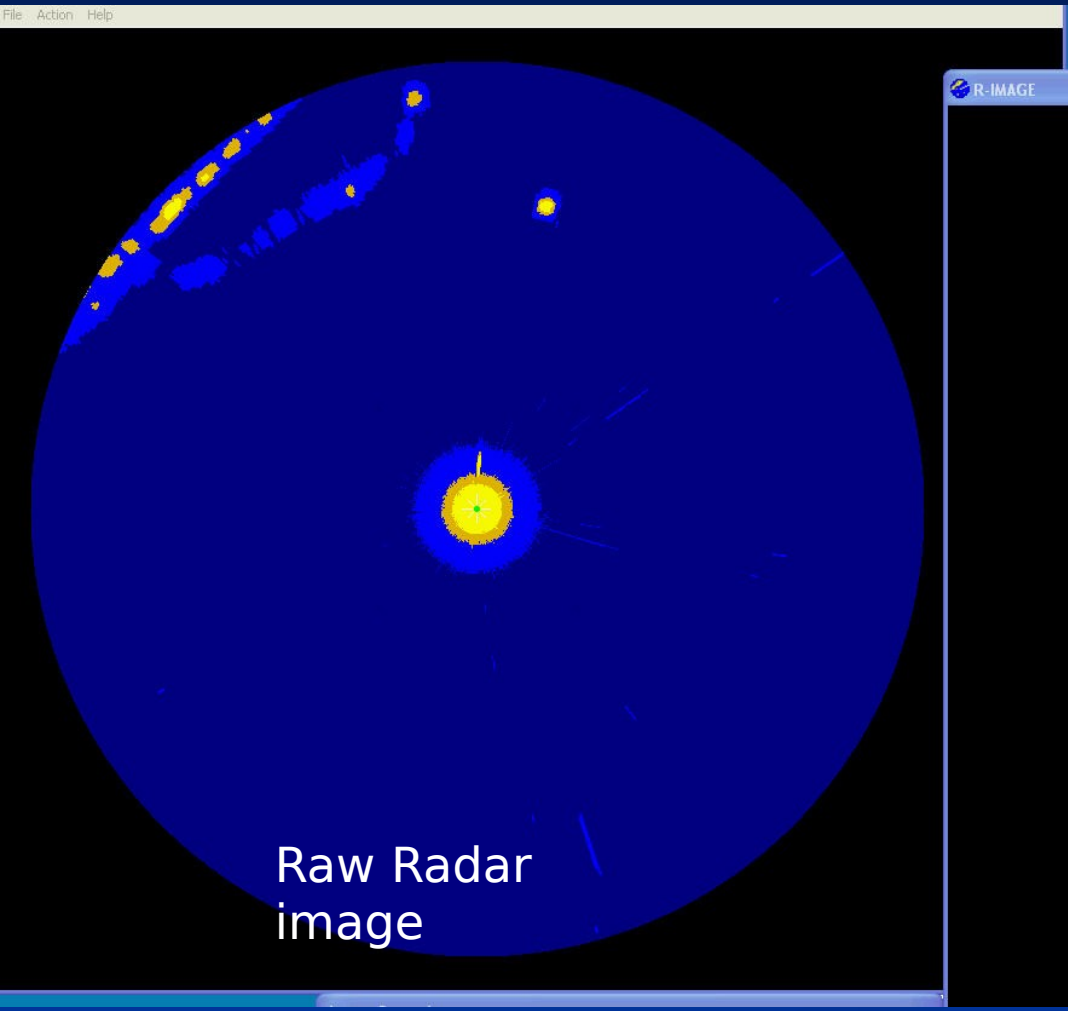
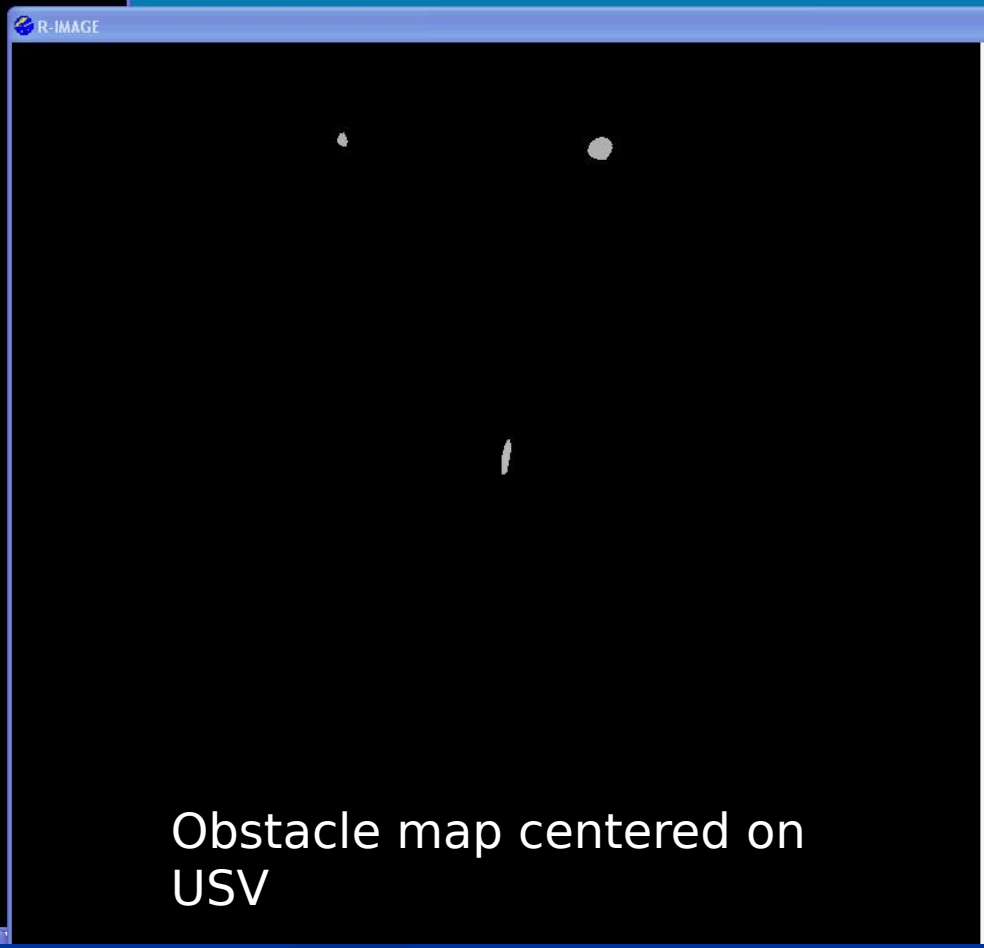
Reactive OA Sensors

Raw Radar – Conversion to Obstacle Map



Raw Radar image



Obstacle map centered on USV

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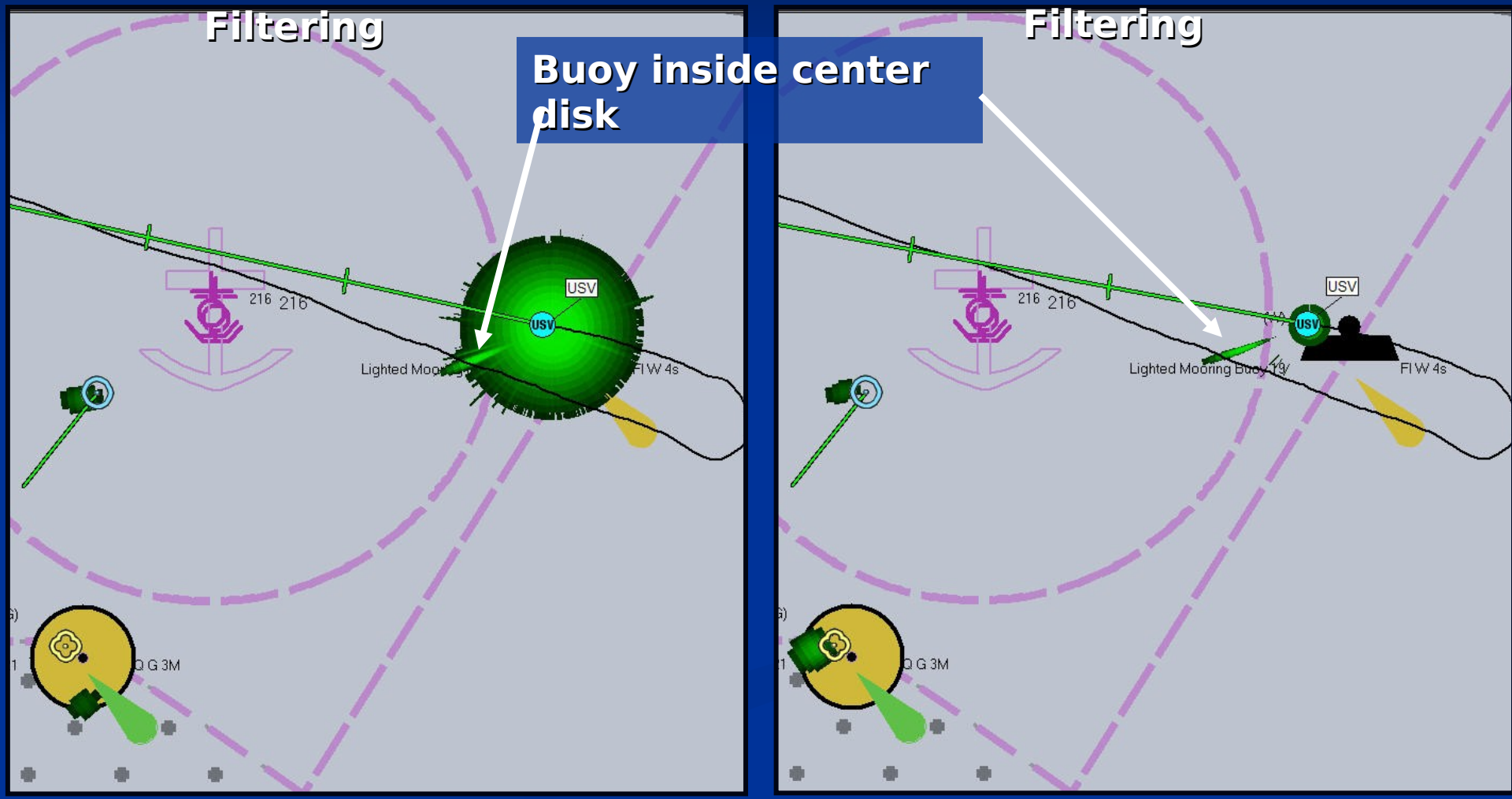
Reactive OA Sensors
Raw Radar – Center Disk

Before Filtering

After Filtering



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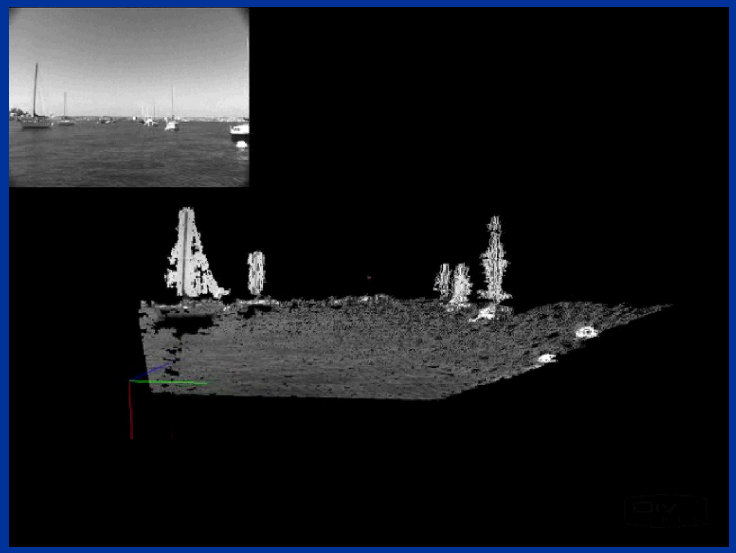
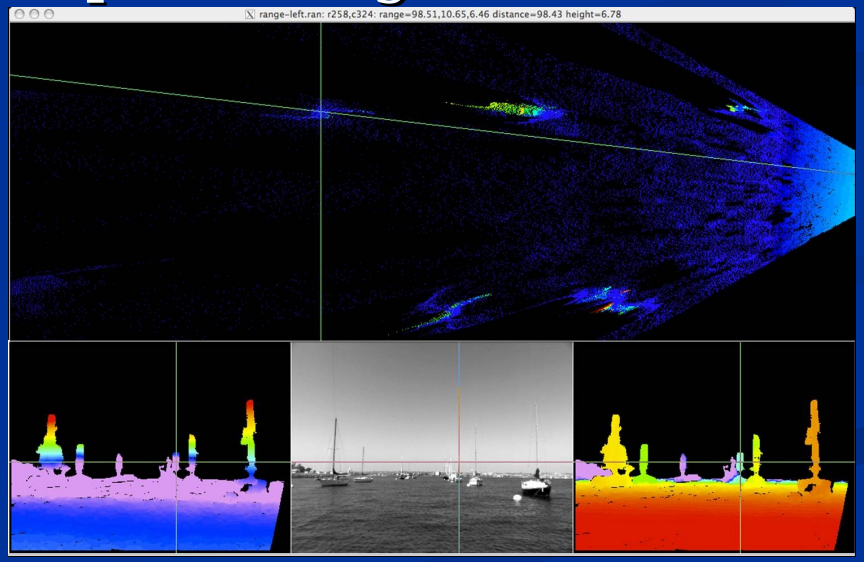
Reactive OA Sensors Stereo Vision

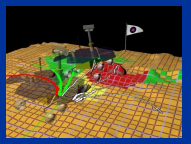
- Leveraging our work with the NASA Jet Propulsion Laboratory on stereo vision for our UGVs
- Collected stereo data on our USV at two different baselines
- Initial results look promising



Provided by the NASA Jet Propulsion Laboratory



Provided by the NASA Jet Propulsion Laboratory



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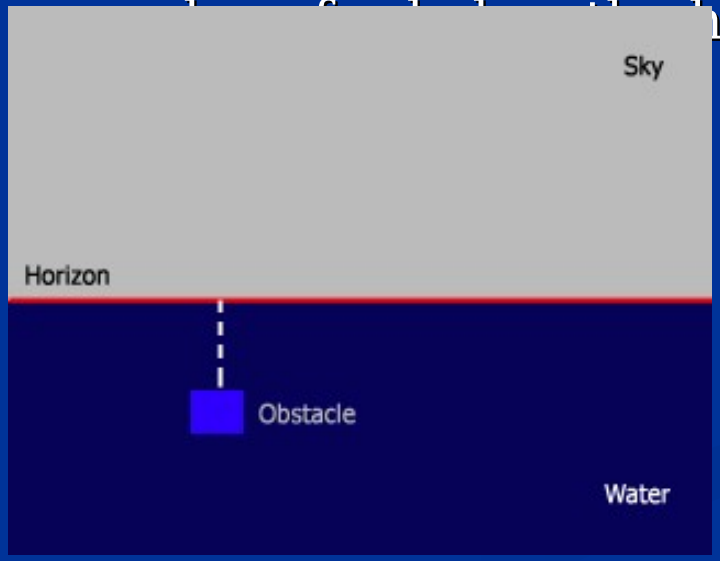
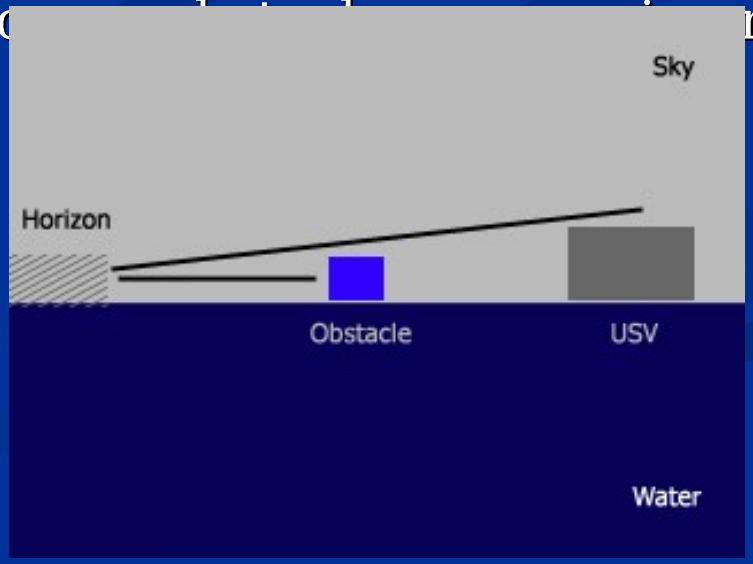
Reactive OA Sensors
Monocular Vision

- Detect obstacle on the water with a single camera
  - Color and texture segmentation, optical flow, etc.
  - Investigating both color and IR cameras
- Detect horizon line
  - Can obtain a rough estimate of range by determining





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Reactive OA Sensors Monocular Vision

- Early results
  - 10 weeks of effort
- Horizon detection in presence of landmass
- Optical flow used to segment objects on water

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Reactive OA Sensors
LADAR

- Preliminary testing with LADAR
  - Limited testing with SICK laser range scanner on water
  - Did not detect water, obstacles only
  - Maximum range of ~80m

Multi-robot Operator Control Unit (MOCU)

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MOCU Features

- Command and control of unmanned vehicles and sensors
- Multi-vehicle support
- Vehicle and protocol type agnostic
- Reconfigurable and dynamic user interface
- Modular architecture (maps, protocols, video, etc.)
- Scalable
- Distributed development

Modular Architecture

Map Modules
- DNC (COGENT)
- C/JMTK (ESRI)
- GeoTIFF

MOCU Core

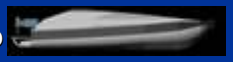
Protocol Modules
- JAUS
- MRHA/SMART
- iRobot Aware

Media Modules
- MJEG
- H.263
- IndigoVision codecs

C2 Link Modules
- JUSC2 UVCC (Spartan)
- Composable Forcenet (CFn)

Programs using MOCU

Spartan ACTD

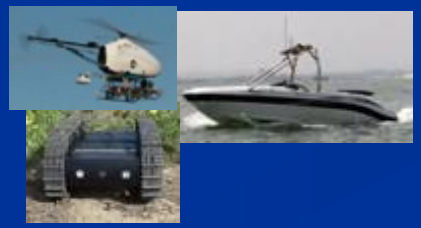


JUSC2 ACTD

FIRRE

U/CAV ACTD

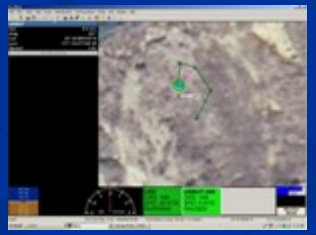
JRP (UGV, USV, UAV)



Reconfigurable User Interface (Dynamic)

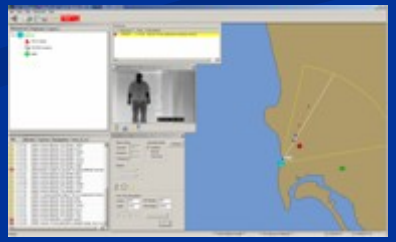
Multi-vehicle Monitor Mode

UGV Control



USV Control

FIRRE Remote Sensor Monitorin



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JAUS UV Standard

- Joint Architecture for Unmanned Systems (JAUS)
  - Originally developed for UGVs under the Joint Robotics Program
    - Moving to an SAE standard
  - SSC extended the standard message set for USVs for the Spartan ACTD
    - That IDD is now being adapted by the LCS USV programs
  - JAUS is not just a C2 to vehicle message set
    - May also be used as a reference architecture for on-board vehicle component messaging
      - Working towards plug-n-play components

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Summary

- A phased approach to autonomy development provides useful building blocks that can be transitioned sequentially
- Two-tiered approach to obstacle avoidance has been proven in other environments and translates well into the USV domain

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Questions?

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